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Can the rapid braking of the white dwarf in AE Aquarii be explained in terms of the gravitational wave emitter mechanism?

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ABSTRACT

The spin-down power of the white dwarf in the close binary AE Aquarii significantly exceeds the bolometric luminosity of the system. The interpretation of this phenomenon in terms of the gravitational-wave emitter mechanism has been recently suggested by Choi & Yi. The basic assumption of their interpretation is that the spatially limited blobs or mounds of the mass $\delta m \sim 10^{-3} M_{\odot}$, are present at the magnetic poles of the white dwarf. We show that the mounds of this mass can be confined by the magnetic field of the white dwarf only if the dipole magnetic moment of the star exceeds $4 \times 10^{37} \text{ G cm}^3$. Under these conditions, however, the magnetodipole losses of the white dwarf would exceed the evaluated spin-down power 6 orders of magnitude. On this basis we discard a possibility that the observed rapid braking of the white dwarf in AE Aqr can be explained in terms of the mechanism proposed by Choi & Yi.

Subject headings: accretion, accretion disks – binaries: close – magnetic fields – white dwarfs

1. Introduction

Rapid braking of the white dwarf in AE Aquarii is one of the most puzzling properties of this low-mass close binary system [for the system parameters and corresponding references

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see Table 1 in Ikhsanov (2000)]. As shown by de Jager et al. (1994), the white dwarf is steady spinning down at a rate $\dot{P} = 5.64 \times 10^{-14} \text{ s s}^{-1}$, which implies the spin-down power of

$$L_{\text{sd}} \cong 6 \times 10^{33} I_{50} \dot{P}_0 P_{33}^{-3} \text{ erg s}^{-1}. \quad (1)$$

Here the parameters I_{50} , P_{33} , and \dot{P}_0 denote the moment of inertia, the spin period, and the spin-down rate of the white dwarf expressed in units of 10^{50} g cm^2 , 33 s, and $5.64 \times 10^{-14} \text{ s s}^{-1}$, respectively.

L_{sd} exceeds the luminosity of the system in the UV and X-rays by a factor of 120, and it even exceeds the bolometric luminosity by a factor of more than 5 [see Table 3 in Eracleous & Horne (1996)]. This means that the spin-down power dominates the energy budget of the system and raises the question about the nature of the spin-down torque, which is much larger than any inferred accretion torque.

Some effort has been made to explain this phenomenon. Wynn, King & Horne (1997) suggested that the white dwarf interacts with the stream of material inflowing from the normal companion and is spinning down due to propeller action. Ikhsanov (1998) has pointed out that the magneto-dipole losses of the white dwarf are comparable with the estimated spin-down power provided its surface magnetic field is $B(R_{\text{wd}}) = 50B_{50} \text{ MG}$:

$$L_{\text{md}} = 5 \times 10^{33} B_{50}^2 R_{8.8}^6 P_{33}^{-4} \text{ erg s}^{-1}, \quad (2)$$

Here $R_{8.8}$ is the radius of the white dwarf expressed in units of $10^{8.8} \text{ cm}$, and the angle between the the rotational and the magnetic axes of the white dwarf is taken according to Eracleous et al. (1994) as $\theta \approx 76^\circ$.

Both these approaches have been recently critically discussed by Choi & Yi (2000), who presented an alternative explanation of the spin-down power. Namely, they have shown that the rapid braking of the white dwarf in AE Aqr can be explained in terms of the gravitational wave emission mechanism provided the spatially limited blobs or mounds of the mass

$$\delta m \sim 10^{-2} [\sin^2 \theta (13 \sin^2 \theta + \cos^2 \theta)]^{-1/2} M_\odot, \quad (3)$$

are present at the magnetic poles of the white dwarf. Putting $\theta = 76^\circ$ we get

$$\delta m(\theta = 76^\circ) \simeq 3 \times 10^{-3} M_\odot. \quad (4)$$

Choi & Yi (2000) have assigned the origin of these mounds to the accretion of material onto the white dwarf surface during the previous spin-up epoch. They assumed that (i) the material accreted by the white dwarf during this epoch impacted the stellar surface preferentially in a local space at the magnetic pole regions and (ii) the amount of this material,

which was confined by the white dwarf magnetic field at the magnetic pole regions, was large enough for the mounds of the mass δm to form. Taking into account that the mass of the material accreted during the spin-up epoch is limited to [see Ikhsanov (1999)]

$$M_{\text{a0}} \gtrsim 3 \times 10^{-2} M_{\odot} \text{ yr}^{-1} I_{50} P_{33}^{-1} M_{0.8}^{-1/2}, \quad (5)$$

the second assumption implies that about 10% of the accreted material was stored in the mounds at the magnetic poles of the white dwarf. Here $M_{0.8}$ denotes the mass of the white dwarf expressed in units of $0.8M_{\odot}$.

In this letter we analyze the validity of these assumptions. We show that the size of the accretion region during the spin-up epoch was almost comparable with the radius of the white dwarf and that the maximum mass of the mounds, which can be confined by the magnetic field of the white dwarf, is smaller than that estimated from Eq. (4) about 11 orders of magnitude.

2. The size of the accretion region

As recognized by Lamb, Pethick & Pines (1973), the size of the accretion spot at the surface of a magnetized compact star can be evaluated as

$$a_{\text{p}} \approx R_{*} \varepsilon_{\text{p}}. \quad (6)$$

Here R_{*} is the radius of the star and ε_{p} is the opening angle of the accretion column, which in the case of the dipole configuration of the stellar magnetic field is

$$\varepsilon_{\text{p}} \simeq (R_{*}/R_{\text{m}})^{1/2}, \quad (7)$$

where R_{m} is the radius of the magnetosphere at the magnetic equator.

For a steady accretion onto the stellar surface to occur the radius of its magnetosphere must be limited to

$$R_{\text{m}} \lesssim R_{\text{cor}} = 1.5 \times 10^9 M_{0.8}^{1/3} P_{33}^{2/3} \text{ cm}, \quad (8)$$

where R_{cor} is the corotational radius and $M_{0.8}$ is the mass of the white dwarf expressed in units $0.8M_{\odot}$. Otherwise, the star is in the centrifugal inhibition regime and no accretion onto its surface occurs [see for discussion Ikhsanov (2001)].

Under these conditions the opening angle of the accretion column of the white dwarf during the previous spin-up epoch can be limited to

$$\varepsilon_{\text{p0}} \gtrsim 0.65 R_{8.8}^{1/2} \left[\frac{R_{\text{m}}}{1.5 \times 10^9 \text{ cm}} \right]^{-1/2} \text{ rad}, \quad (9)$$

and, correspondingly, the size of the accretion region can be estimated as [see Eq. (6)]

$$a_{p0} \approx 4.2 \times 10^8 R_{8.8}^{3/2} \left[\frac{R_m}{1.5 \times 10^9 \text{ cm}} \right]^{-1/2} \text{ cm}. \quad (10)$$

The obtained value of a_{p0} is only a factor of 1.5 smaller than the radius of the white dwarf. In this case, the mounds cannot be considered as spatially local blobs and hence, the validity of the equation (3.4) in Choi & Yi (2000) is rather questionable.

3. Upper limit to the mass of the mounds

The stellar magnetic field is able to prevent the accreting plasma from spreading around the stellar surface if the energy density of the field is larger than the gas pressure in the mounds, i.e.

$$\frac{B_*^2}{8\pi} > \frac{1}{2} \rho_m V_s^2. \quad (11)$$

Here B_* is the magnetic field strength in the magnetic pole regions at the surface of the white dwarf, ρ_m is the plasma density in the mounds, and $V_s = \sqrt{\gamma k T / m_p}$ is the sound speed. γ , k and m_p denote the adiabatic index, the Boltzmann constant and the proton mass, respectively.

This means that the plasma density in the mounds can be limited to

$$\rho_m < \rho_{\max} \simeq 10^{-6} \mu_{32}^2 R_{8.8}^{-6} T_8^{-1} \text{ g cm}^{-3}, \quad (12)$$

where μ_{32} is the magnetic moment of the white dwarf expressed in units of 10^{32} G cm^3 and $T_8 = T_m / 10^8 \text{ K}$ is the temperature in the shock at the base of the accretion column, which is normalized according to the results of Eracleous, Halpern and Patterson (1991). Hence, as soon as ρ_m increases above ρ_{\max} , the magnetic field can no longer balance the pressure of plasma in the mounds and thus, the material accumulated in the magnetic pole regions is able to spread around the surface of the white dwarf.

The maximum mass of mounds, which can be confined by the magnetic field at the magnetic pole regions, can be estimated using Eqs. (10) and (12) and assuming the radial distribution of plasma density in the mounds to be barometric. Under this assumption the maximum mass of mounds is

$$\begin{aligned} \delta m_{\max} &\simeq \pi a_p^2 \int_0^{r_{\text{cor}}} \rho_{\max} e^{-(r/h_m)} dr \sim \pi a_{p0}^2 \rho_{\max} h_m \\ &\simeq 1.5 \times 10^{-14} \mu_{32}^2 M_{0.8}^{-1} R_{8.8}^{-1} \left[\frac{R_m}{1.5 \times 10^9 \text{ cm}} \right]^{-1} M_{\odot}. \end{aligned} \quad (13)$$

Here $h_m = V_s^2/g$ is the height of the homogeneous atmosphere in the mounds and $g = GM_{\text{wd}}/R_{\text{wd}}^2$ is the gravitational acceleration at the surface of the white dwarf.

Comparing Eqs. (4) and (13), one can see that for the mounds of the mass $3 \times 10^{-3} M_\odot$ to be confined by the magnetic field, the magnetic moment of the white dwarf should be in excess of $4 \times 10^{37} \text{ G cm}^3$, which implies the strength of the surface field of the star $4 \times 10^{10} \text{ G}$. Under these conditions, however, the magneto-dipole losses by the white dwarf would exceed the evaluated spin-down power six orders of magnitude [see Eq. (2)].

On the other hand, if the magnetic moment of the white dwarf is $\sim 10^{32} \text{ G cm}^3$, as adopted by Choi & Yi (2000), the mass of mounds required to explain the observed spin-down of the white dwarf within the gravitational wave emitter mechanism is larger than the maximum possible mass of mounds, which can be confined by the white dwarf magnetic field, by roughly 11 orders of magnitude.

Even assuming that the radial distribution of plasma density in the mounds is $\rho(r) \sim r^{-3}$, i.e. the same as the radial distribution of the dipole magnetic field of the star, one finds the maximum possible mass of mounds as $2 \times 10^{-13} M_\odot$. This is still about ten orders of magnitude smaller than that required within the approach of Choi & Yi (2000).

Finally, the size of the accretion region, a_{p0} , is estimated under the assumption that the accretion flow onto the surface of the white dwarf is steady and homogeneous. In the case of inhomogeneous accretion, the size of the accretion region depends on the parameters of blobs and may differ from the value estimated by Eq. (10). However, if the radius of blobs is larger than a_{p0} , the size of the accretion region proves to be comparable with the radius of the white dwarf. In this case the equation (3.6) of Choi & Yi (2000) turns out to be not applicable. On the other hand, if the size of the accretion region is smaller than that estimated in our paper, the density as well as the gas pressure in the mounds of the same mass are larger. Therefore, for these mounds to be confined, the magnetic field of the white dwarf should be even stronger than that estimated above.

Thus, we are forced to conclude that the mounds of the mass estimated by Eq. (4) cannot exist on the surface of the white dwarf and, hence, the approach presented by Choi & Yi (2000) is not applicable for the interpretation of the observed rapid braking of the white dwarf in AE Aquarii.

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